New Techniques in Steel Meltshop Air Pollution Control

Steel meltshop air pollution control systems rely on fourth-hole direct extraction from the arc furnace and canopy extraction above the furnace. The general design approach aims for a combined gas temperature from the fourth hole and canopy suitable to low temperature filtration (< 120°C). Increases in furnace productivity (reduction in tap-to-tap times) and changes in chemical energy (increased carbon injection) have generally resulted in large increases in filtration capacity being required.

This article outlines recent work to improve extraction efficiency from the fourth hole. Practical tests were conducted to develop profiles of offgas temperature, gas composition and flowrates over the period of a melt. The values were related back to theoretical offgas energies, and heat transfer over the offgas system was correlated with theoretical models. The above elements were subsequently combined to develop an operating profile of temperatures over a range of extraction volumes, resulting in an operating point where full evacuation of the furnace occurs.

Process Description

During 2006, a study was done on the air pollution control (APC) system at a steel meltshop. The furnace maximum power input was 80 MW, with a power-on time of 34 minutes and a total scrap charge mass of 130 tons, charged in three batches. Chemical energy was supplied by carbon, oxygen, air and methane injection.

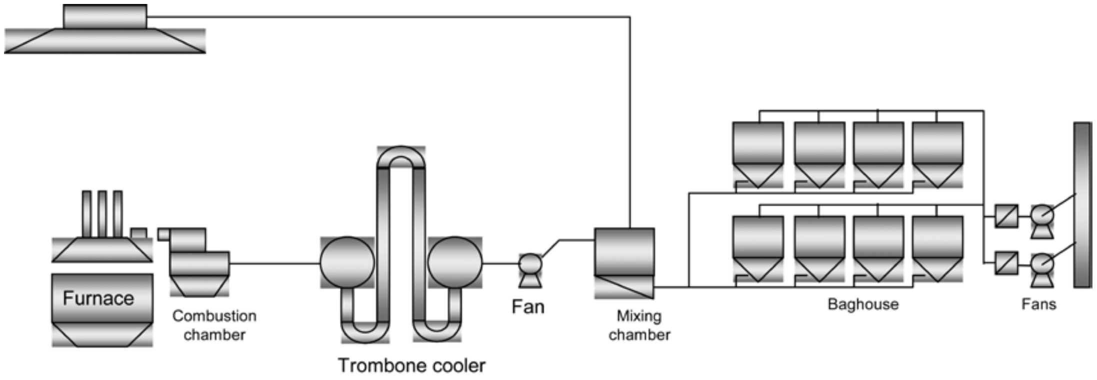
This article outlines recent work done to improve extraction efficiency from the fourth hole. Practical tests were performed to develop profiles of offgas temperature, gas composition and flowrates over the period of a melt.

The charge mass initial design was for 100 tons. Production rates had been increased by 30%, without any modifications to the APC system. As a consequence, the building's ambient air quality was poor, with dense fume, low visibility and high ambient temperatures in the upper levels of the building. The layout of the APC system from the meltshop is shown in Figure 1.

A brief system description is as follows:

- An electric arc furnace (EAF) is served by both direct evacuation (fourth-hole extraction) and canopy hood.

Figure 1



Steel meltshop APC system layout.

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Table 1

APC System Design

	Melting Canopy	Melting Fourth hole	Melting Stack flow	Charging/tapping Canopy	Charging/tapping Fourth hole	Charging/tapping Stack flow
Total gas flow						
Am3/h	323,000	575,000	698,000	1,600,000	—	1,600,000
Nm3/h	265,000	180,000	485,000	1,200,000	—	1,200,000
Temperature, °C	50	600	120	80	—	80

- The EAF direct evacuation offgas is combusted and cooled in a water-cooled duct section prior to further cooling in a trombone cooler. A booster fan serves the direct furnace duct.
- Gas from the furnace duct and canopy hood is mixed in a chamber prior to being filtered in a multi-compartment reverse pulse baghouse. The baghouse is fitted with polyester bags, which have a maximum operating temperature of 120°C.
- Two fans serve the baghouse, and the cleaned gas is subsequently emitted via a stack.

The extraction design for melting and charging periods is summarized in Table 1.

During melting, APC system performance was constrained by high baghouse inlet temperatures, which resulted in the booster fan being operated at lower than design speed and consequent low extraction efficiency at the fourth hole. Air quality problems in the building were caused to a large extent by furnace emissions during the melt period.

To evaluate the problem and suggest improvements, the following actions were undertaken:

- The system was tested to determine APC current performance and compare to initial design parameters.
- Offgas modelling calculations were performed to validate test figures, predict APC performance under various operating scenarios, and evaluate possible solutions.
- Computational fluid dynamics (CFD) modeling was performed to evaluate APC extraction efficiency under both charging and melting scenarios, and the impact thereof on building air quality.

Site Test Work

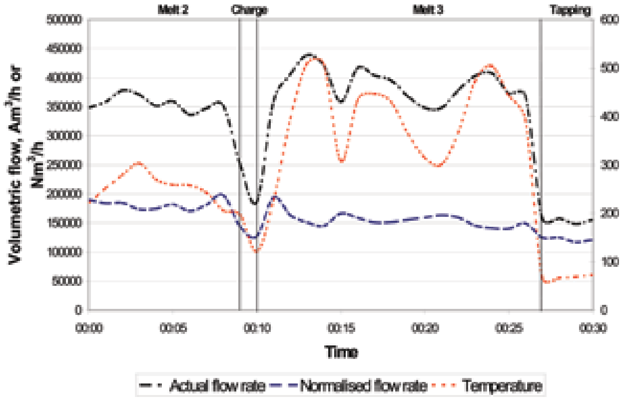
Volumetric flow tests were done at the furnace's fourth hole extraction at a position between the water-cooled ducting and the trombone cooler inlet. The following parameters were logged in real time:

- Velocity and static pressure.
- Gas temperature.
- Gas composition: CO_2 content.

Tests were done at two booster fan speeds: 800 and 900 rpm (both lower than the original design of 1,000 rpm). This was due to the baghouse inlet temperature limitation.

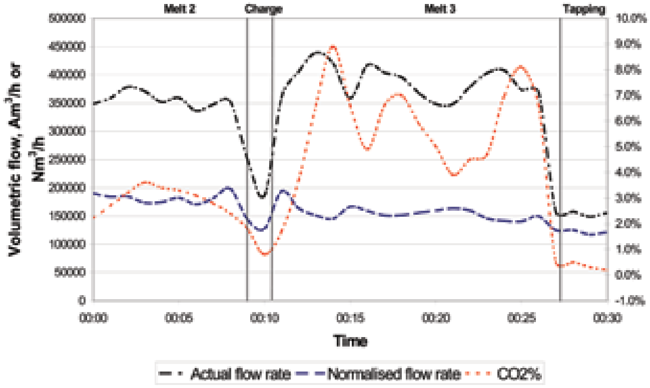
Test Results: 800-rpm Booster Fan Speed — The actual gas flow, normalized gas flow, CO_2 content, offgas temperature and calculated offgas energy are shown in Figures 2–4 over the period of one blow. Figure 5 shows

Figure 2



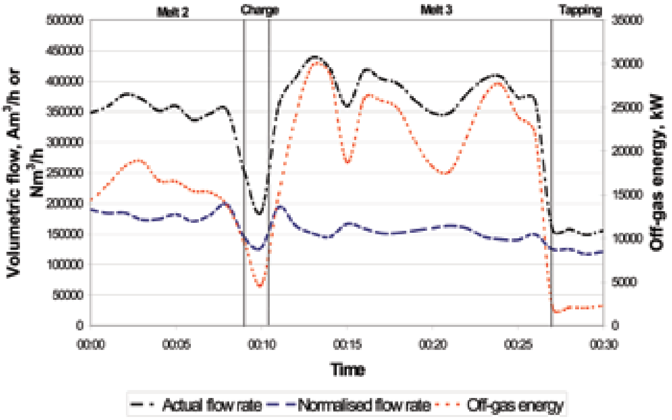
Actual flow, normalized flow and temperature.

Figure 3



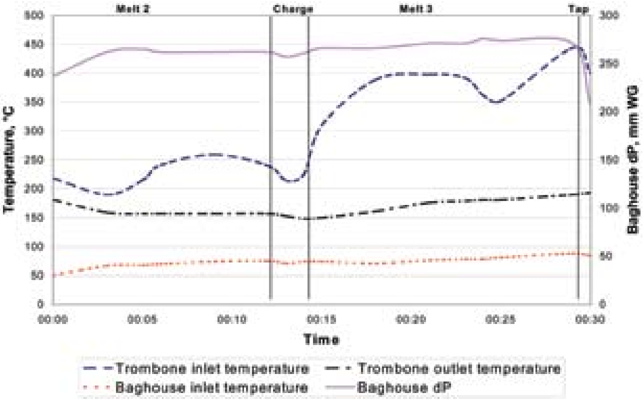
Actual flow, normalized flow and CO_2 content.

Figure 4



Actual flow, normalized flow and offgas energy.

Figure 5



APC system operating data.

baghouse plant data during the corresponding period.

The results for operation at 800-rpm booster fan speed indicated the following:

- Offgas actual flowrate varied with temperature from 350,000 to 440,000 Am^3/hour over melting periods.
- Normalized flowrate exceeded 150,000 Nm^3/hour during melting period 2, but as the offgas system heated up during melt 3, it dropped to 120,000 Nm^3/hour.
- Offgas temperature peaked over 500°C during melting period 3.
- The offgas CO_2 content peaked at 9% during melt 3.
- Offgas energy as measured at the end of the water-cooled duct section went up to 30 MW during melt 3.
- Baghouse differential pressure slowly increased over the melt 3 period to more than 250 mm WG.
- Baghouse inlet temperature increased over the melt period to about 90°C at the end of melt 3.

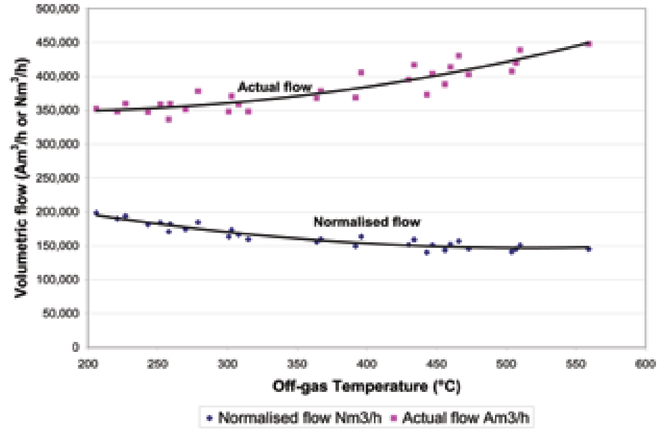
A feature of the above data is that, with increased offgas energy and offgas temperature, the normalized extraction (effectively the mass of gas extracted) decreases. The net effect is reduced extraction efficiency and higher emissions into the building. This is illustrated in Figure 6: higher furnace duct temperatures show a correlation with increased actual flowrate and decreased normalized flowrate.

Test results: 900-rpm Booster Fan Speed — The equivalent test result graphs are shown in Figures 7–10 for operation at 900-rpm booster fan speed.

The results for operation at 900-rpm booster fan speed indicated the following:

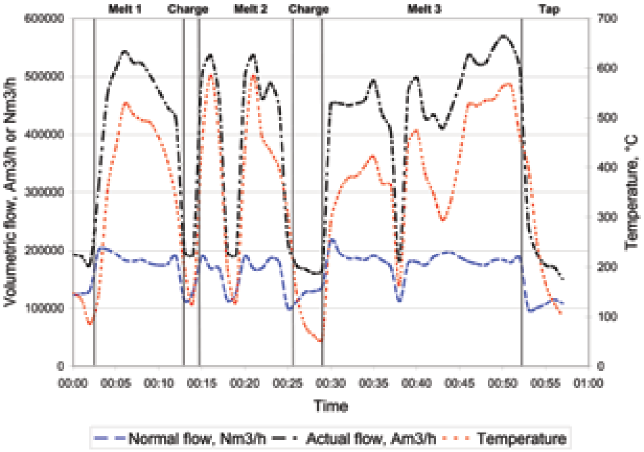
- Offgas actual flowrate varied with temperature from 450,000 to 550 000 Am^3/hour over melting periods.

Figure 6



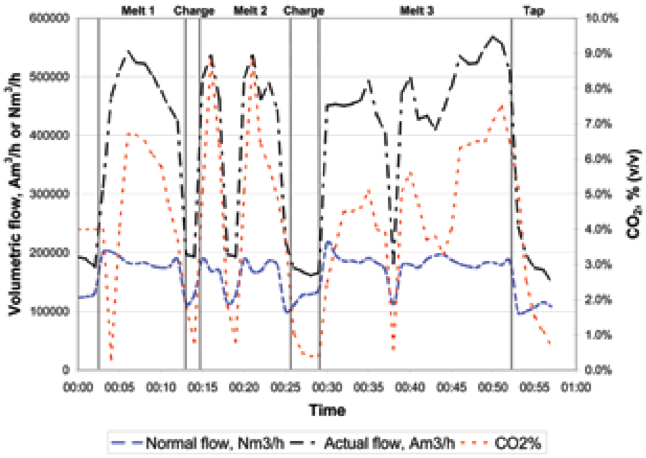
Temperature correlation — actual vs. normalized flow.

Figure 7



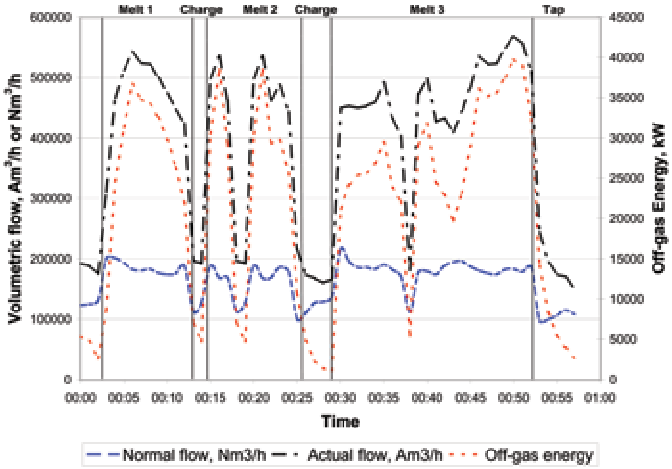
Actual flow, normalized flow and temperature.

Figure 8



Actual flow, normalized flow and CO$_2$ content.

Figure 9



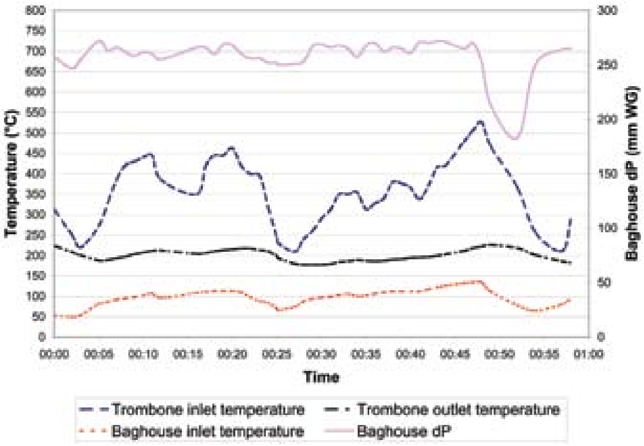
Actual flow, normalized flow and offgas energy.

- Normalized flowrate was consistently around 180,000Nm^3/hour.
- Offgas temperature peaked just below 600°C.
- The offgas CO$_2$ content peaked at 9%.
- Offgas energy as measured at the end of the water-cooled duct section went up to 40 MW.
- Baghouse differential pressure slowly increased over the melt 3 period to above 250 mm WG.
- Baghouse inlet temperature increased over the melt period to 130°C at the end of melt 3.

In summary, the higher booster fan speed had the following effects on the APC system:

- Normalized extraction rate increased from between 120,000 and 150,000 Nm^3/hour at 800 rpm to 180,000 Nm^3/hour at 900 rpm.
- Peak offgas temperature increased from 500 to 600°C.
- Peak offgas energy increased from 30 to 40 MW.

Figure 10



APC system operating data.

Baghouse inlet temperature was, however, a limiting factor due to the maximum operating temperature of < 120ºC for polyester filter bags.

Offgas Modeling

Background — The purpose of offgas modeling is to evaluate the effect of various operating scenarios on the offgas system and furnace extraction efficiency. Furnace and offgas modeling is done in two steps:

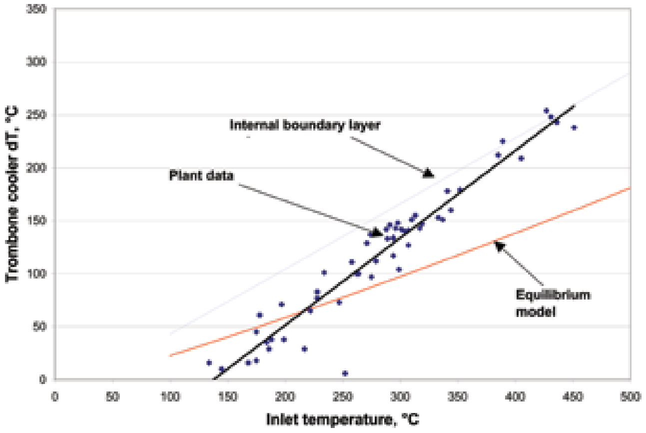
- The furnace offgas volume and offgas energy is estimated using the South African Council of Mineral Technology's (Mintek) Pyrosim program.
- The temperature profile of the gas is calculated throughout the offgas system by estimating heat transfer over the ducting and trombone cooler.

For the steel furnace model, the Pyrosim program was set up in three equilibrium phases: burners, the furnace metal-gas equilibrium and offgas combustion. Thermodynamic equilibrium was calculated in each of the three phases. Based on the thermodynamic modeling as well as the test results, furnace energy to offgas was estimated.

The temperature profile over the offgas system was calculated as follows:

- Furnace offgas flow and temperature were used as input parameters.
- Heat loss over the water-cooled duct, interconnecting ducting and trombone cooler was estimated.
- Dilution effect of air from the canopy hood was calculated to determine the baghouse inlet gas temperature and volumetric flow.

Figure 11



Plant trombone cooler performance vs. calculation results.

A standard trombone cooler design procedure was used, as proposed in the EPA's Air Pollution Engineering Manual.[1] The calculation model makes use of the following correlations:

- Convection heat transfer on the tube inside is estimated through a correlation by Sieder and Tate.[2]
- Radiation heat transfer is estimated through a correlation by McAdams.
- Convection heat transfer on the tube outside is estimated through a correlation by McAdams.[3]

During site testing, it was found that the above procedure did not correctly predict the temperature drop over the trombone cooler. The variance between observed and predicted performance was attributed to the fact that the trombone cooler does not operate continuously at high temperatures. Long periods of lower gas inlet temperatures are experienced with short periods of high gas inlet temperatures during the refining stage of melting. At lower gas inlet temperatures, the cooler acts as a heat sink and absorbs energy to increase steel temperature when exposed to higher gas inlet temperatures. To solve this problem, the modeling procedure was modified to take only the internal boundary layer into account (i.e., neglect resistance to heat transfer at the tube outer boundary layer). To illustrate the above, Figure 11 shows the following:

- Plant operation data points of trombone inlet gas temperature vs. temperature differential over cooler.
- Results of calculations using the conventional equilibrium model, taking internal and external boundary layers into account.
- Results of calculations using the internal boundary layer only and neglecting the external boundary layer.

The important period to correctly predict is when high inlet temperatures are experienced and the baghouse is exposed to maximum energy from the furnace. Figure 11 indicates that, at higher inlet temperatures, the modified cooler model is accurate in predicting cooler efficiency.

Modeling Results — The results of Pyrosim modeling are summarized in Table 2.

The furnace burner energy input (or chemical energy to the furnace) was calculated at

Table 2

Pyrosim Modeling Results

Parameter	Unit	Reaction gas*	Combusted gas**
Gas flowrate	kg/h	11,295	294,295
	Nm^3/h	8,586	225,000
Gas temperature	°C	1,600	393
Gas composition			
CO	% (v/v)	83.4	0.0
CO_2	% (v/v)	10.2	3.6
O_2	% (v/v)	0.0	18.6
N_2	% (v/v)	5.4	77.7
H_2O	% (v/v)	0.6	0.1

* Reaction gas: furnace burner gas

**Combusted gas: combustion chamber offgas

Table 3

Offgas Modeling Results

Furnace duct volumetric extraction, Nm3/hour	145,000	185,000	225,000
Offgas energy, MW (at water-cooled duct outlet)	30	40	52
Combustion chamber outlet temperature, °C	602	742	744
Water-cooled duct outlet temperature, °C	477	595	601
Trombone cooler inlet temperature, °C	457	572	580
Trombone cooler outlet temperature, °C	208	265	276
Baghouse inlet temperature, °C	92	122	154

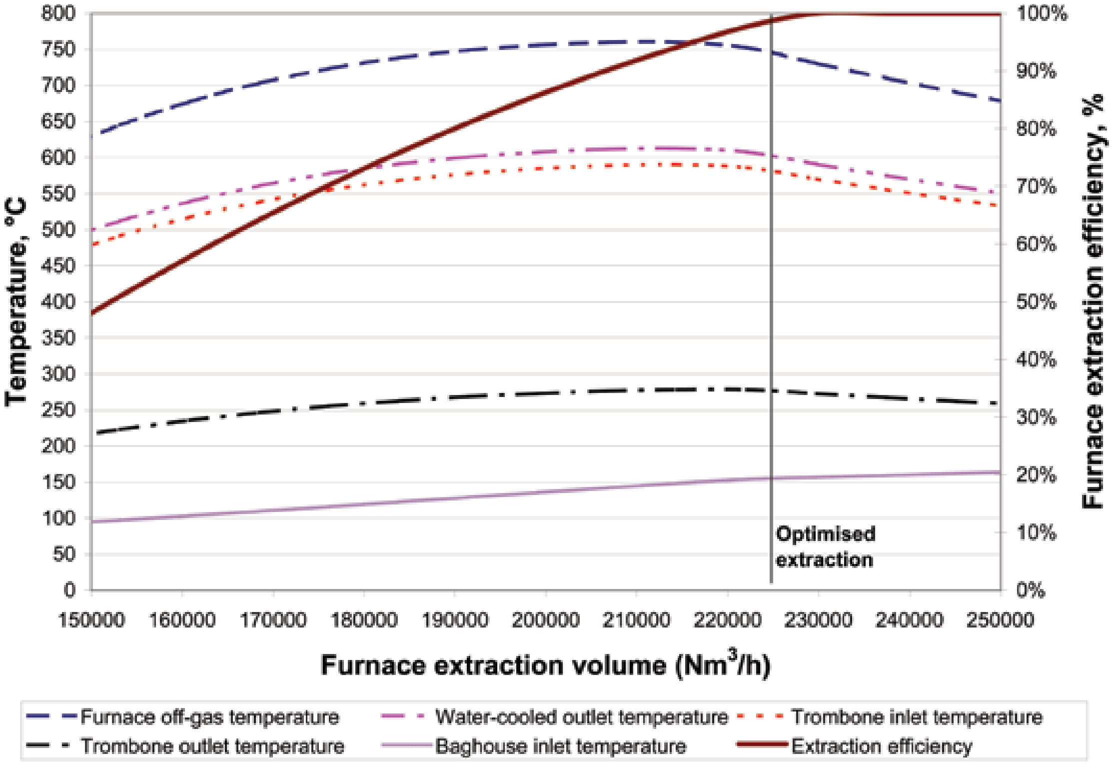
8.2 MW (based on products of combustion at 1,600°C). The energy released in the combustion chamber by CO combustion was 31.1 MW. The above modeling results serve as an average over the refining period. Instantaneous energy release, especially at the end of the refining period just prior to tapping, is much higher than the calculated average. Based on the modeling, test results and a benchmarking exercise, a maximum furnace offgas energy of 65 MW was estimated (which translates to 52 MW at the outlet of the water-cooled duct section).

For the purpose of offgas modeling, the amount of energy extracted from the furnace was assumed to increase with volumetric extraction, as found in the site test results. The test and modeling data was combined to predict offgas system temperatures for three extraction rates at the furnace duct:

- 800-rpm test case: 145,000 Nm^3/hour, 30 MW offgas energy at water-cooled duct outlet.
- 900-rpm test case: 185,000 Nm^3/h, 40 MW offgas energy at water-cooled duct outlet.
- Maximum offgas energy case: 225,000 Nm^3/hour, 52 MW offgas energy at water-cooled duct outlet.

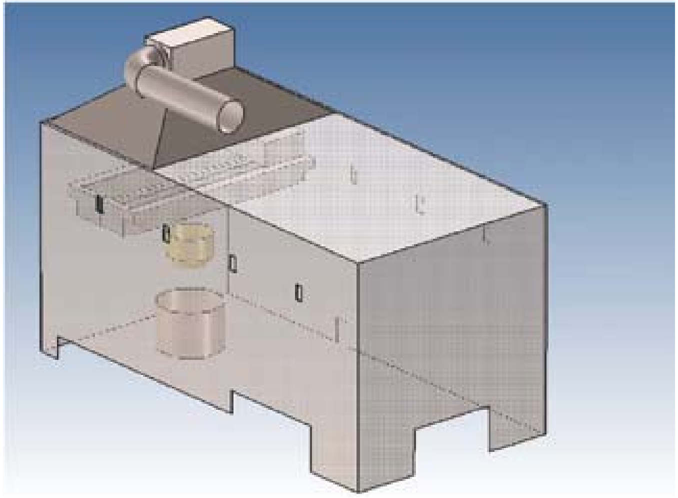
The offgas system temperature profile calculated above was extended over a furnace duct extraction range of 150,000 to 250,000 Nm^3/hour. The system temperature profile is illustrated in Figure 12.

Figure 12



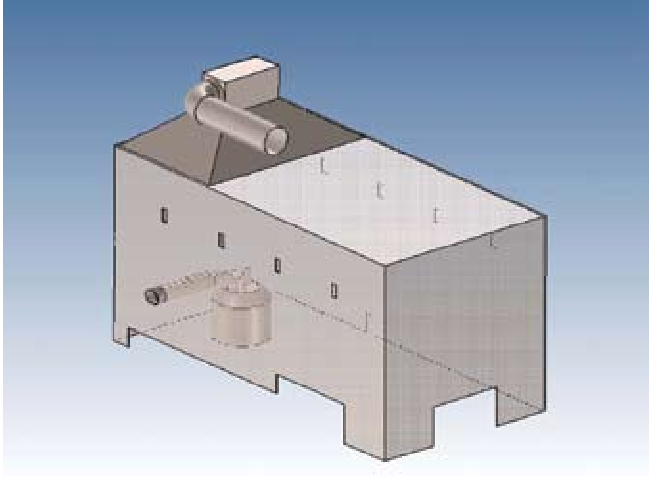
Furnace offgas modeling results: temperature profile and extraction efficiency.

Figure 13



Charging model.

Figure 14



Melting model.

Figure 12 indicates the following:

- As furnace extraction increases, offgas energy is more effectively captured at the furnace, and the combustion chamber temperature increases from 640 to 750°C.
- The water-cooled duct outlet temperature similarly increases from 500 to 600°C, as does the trombone inlet temperature.
- The trombone outlet temperature increases to 270°C, and the baghouse inlet temperature increases to 154°C.
- Increased efficiency of offgas energy capture means that smoke and flames at the furnace are minimized.
- As the furnace duct extraction rate is increased, furnace emissions are minimized. Optimum extraction efficiency is reached at 225,000 Nm^3/hour.

Meltshop Computational Fluid Dynamics Modeling

Canopy hood design techniques are generally based on the assumption that conduction and convection from a hot surface cause buoyant air flows.[4–5] A canopy hood is then installed directly above the source to capture the contaminant plume. These design techniques have the following limitations when applied to steel meltshop ventilation:

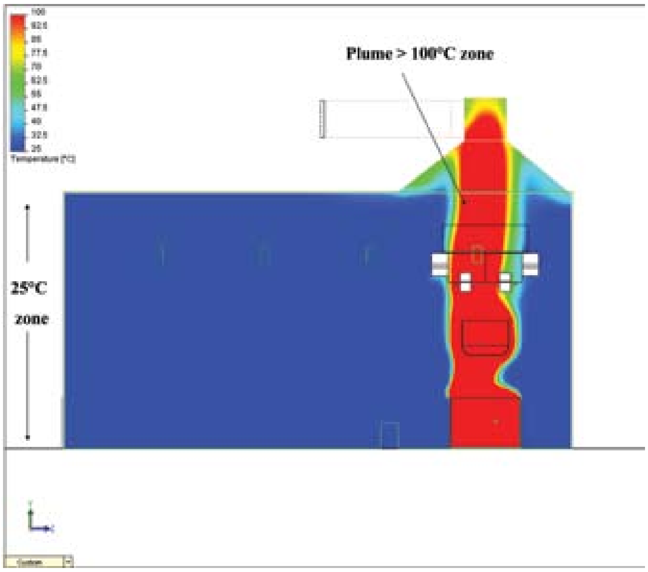
- Energy release from the furnace, during either charging or melting, is in the form of a high-temperature gas source that has an initial upward velocity and that does not rely on convection or conduction mechanisms.
- Meltshop layout complicates canopy design: the crane and charging basket are in position above the furnace; canopy positioning and sizing are frequently non-optimal due to building design factors.
- The effect of building cross-drafts, doors and other openings, as well as external wind conditions cannot be taken into account.

Computational fluid dynamics (CFD) modeling allows a more comprehensive evaluation of canopy hood design and other measures to improve building air quality. In order to illustrate this technique, modeling was done for both charging and melting periods. A 3-D model of the meltshop building was constructed in IronCAD, which was transferred to EFD Lab version 7.0 CFD software. The building models for charging and melting are shown in Figures 13–14.

The charging model has the furnace without roof, with a basket and crane above the furnace. The melting model has the furnace complete with roof, electrodes and fourth-hole extraction ducting.

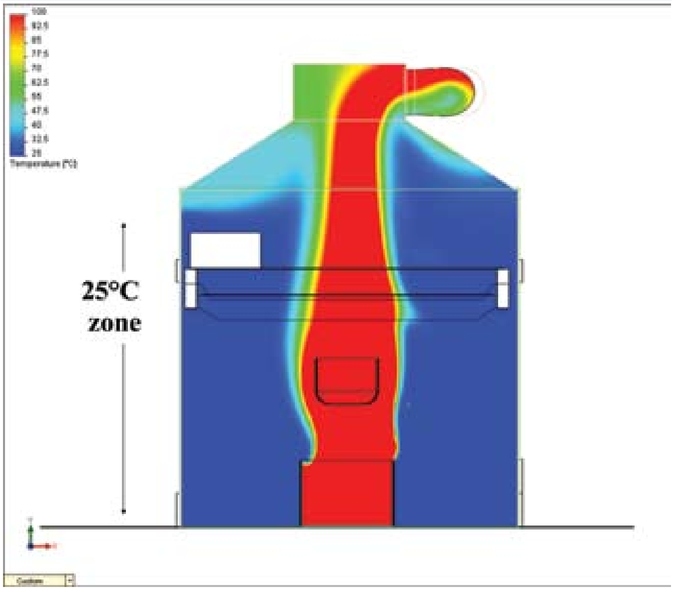
As mentioned above, the total charge mass was increased from 100 to 130 tons of scrap, charged in three batches. CFD modelling was used to evaluate the effect of the charging operation on building air quality. To this end, the quantity of air entrained in the falling scrap during charging was calculated, and the hot gas plume generated by charging was based on this amount of air, combusted with any oil in the scrap or carbon residual in the furnace. Below, design canopy extraction volumes were applied to two charging cases: 100 tons (Figures 15 and 16) and 130 tons (Figures 17 and 18). The figures show a vertical cut-plot of temperature through the furnace building, over a range of 25–100°C. The building temperature profile is a good indication of fume extraction efficiency: hot

Figure 15



Charging 100 tons, elevation 1.

Figure 16



Charging 100 tons, elevation 2.

gas is associated with fume particulate, and any areas with higher than ambient temperatures can be expected to be hot and dirty.

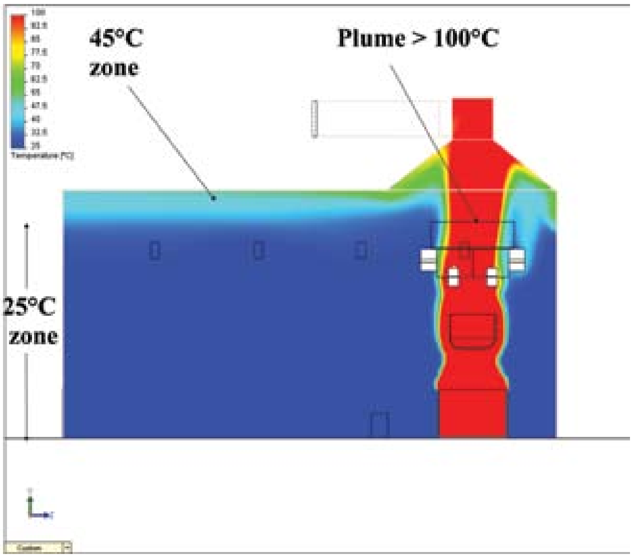
The original design cases show that canopy extraction is sufficient to extract the charge plume: temperatures are high in the path of the plume above the furnace to the canopy hood, but fume is adequately extracted and does not spread to the rest of the building.

A slight deterioration in the canopy fume extraction efficiency is evident in Figures 17 and 18 for 130-ton charging: air temperatures of 40–50°C occur just below the roof level. Overall, the building air quality is adequate, with most of the elevation temperatures being around 25°C. The original design canopy extraction volume is therefore sufficient to deal with the increased charge mass.

The results of CFD modelling for the melting condition are evaluated for the following cases:

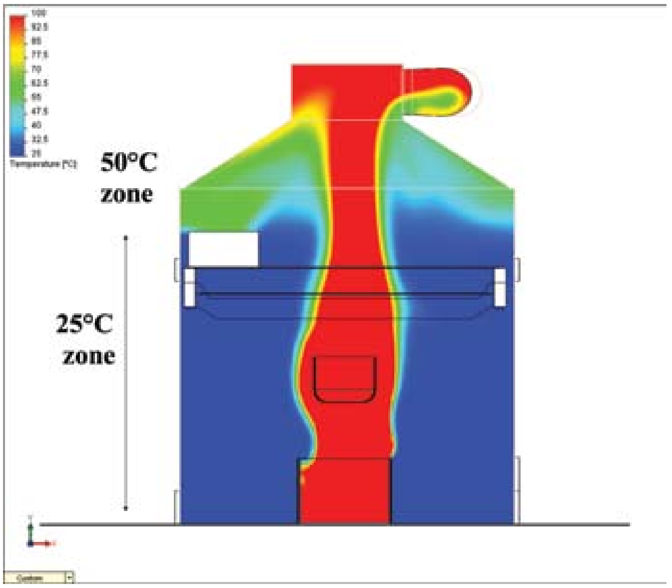
- Case 1: This case focuses on the original design fourth-hole extraction volume, but with the increased furnace offgas energy caused by the higher furnace power input.

Figure 17



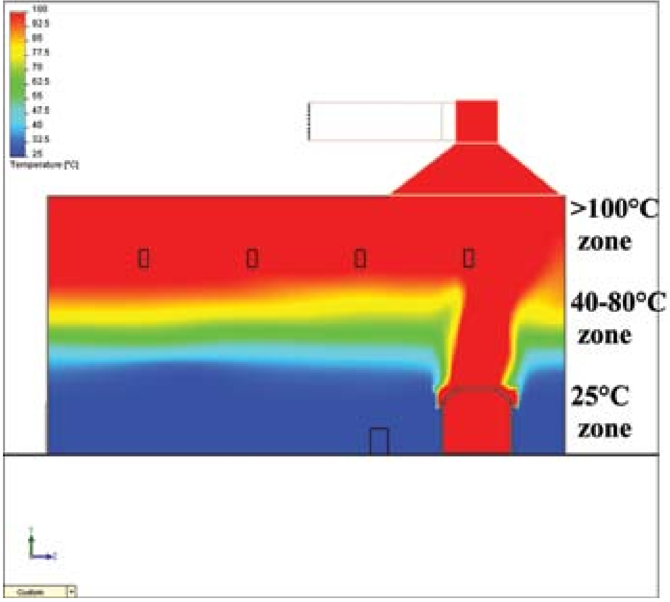
Charging 130 tons, elevation 1.

Figure 18



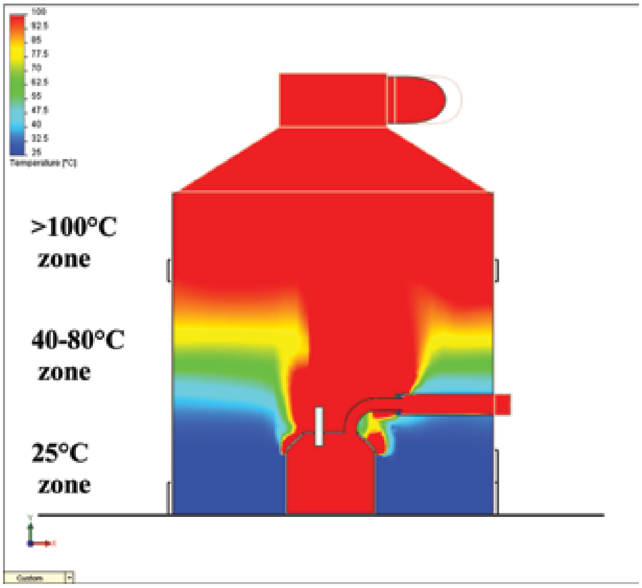
Charging 130 tons, elevation 2.

Figure 19



Case 1 — Original extraction, increased production, elevation 1.

Figure 20

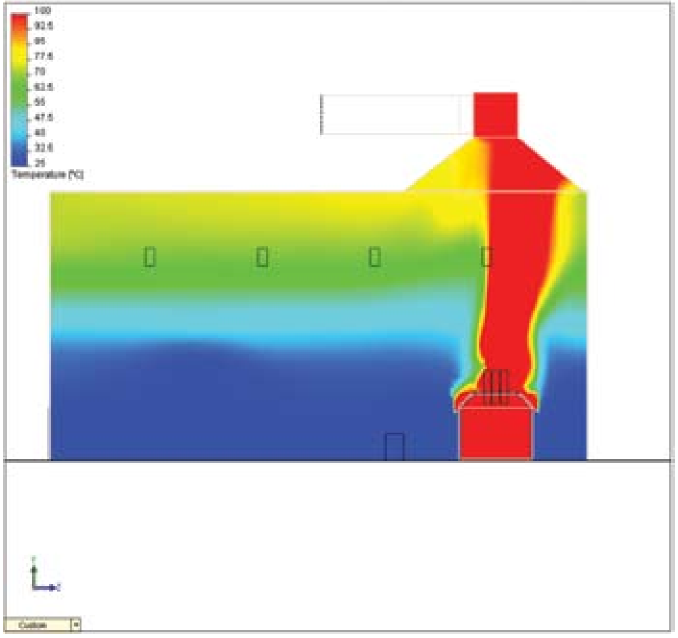


Case 1 — Original extraction, increased production, elevation 2.

- Case 2: Maximum extraction during melting, while staying within low-temperature baghouse constraint. This consists of running main fans at maximum speed during melting, attempting to maximize the canopy extraction to clear the building. Because of the increased canopy volume, additional offgas energy can be extracted from the furnace, while still remaining within the baghouse temperature limit of 120°C.
- Case 3: High-temperature approach. Here, the canopy extraction volume was reduced and fourth-hole extraction was boosted to extract most of the offgas energy.

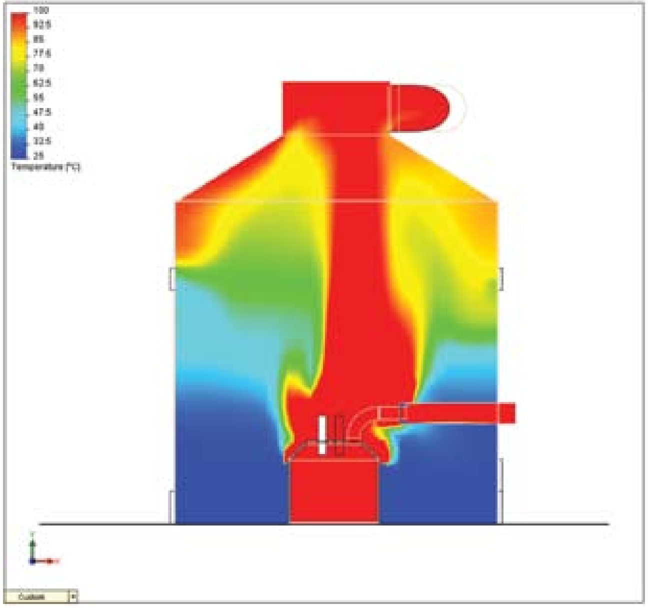
Case 1 results are illustrated in Figures 19 and 20.

Figure 21



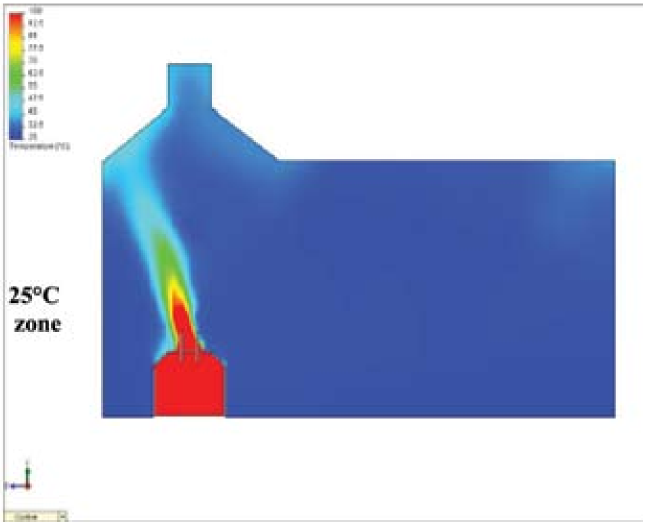
Case 2 — Increased extraction, elevation 1.

Figure 22



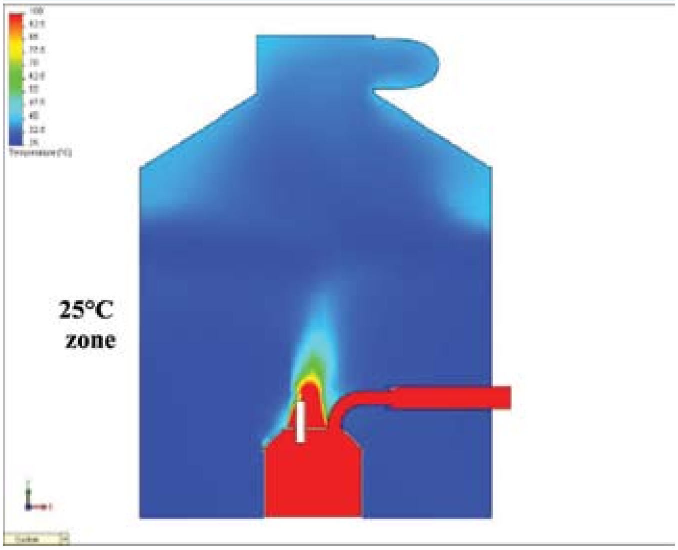
Case 2 — Increased extraction, elevation 2.

Figure 23



Case 3 — High-temperature approach, elevation 1.

Figure 24



Case 3 — High-temperature approach, elevation 2.

Results in Case 1 predict building temperatures of above 100°C in the top half of the building. Pollution in the building is therefore dire, and general working conditions completely untenable.

The general response of site personnel to the Case 1 scenario is to run the main fans at maximum speed during melting, attempting to increase both the canopy extraction and the fourth-hole extraction. The limitation of the baghouse inlet temperature requirement of 120°C has to be met. This is shown in Case 2 in Figures 21 and 22.

Results in Figures 21 and 22 indicate that the building conditions are mitigated somewhat: temperatures are reduced to between 40 and 80°C in the upper levels of the building. Working conditions are still poor, but improved from the Case 1 scenario.

Case 3 highlights the high-temperature approach: the furnace is still run at a slight positive pressure, but most of the offgas energy is removed by the fourth-hole extraction.

Case 3 results (Figures 23 and 24) show that, by extracting most of the fume at source and not allowing dispersion of fume, the building air quality is substantially improved: temperatures are maintained below 30°C in most areas not directly above the furnace.

The high-temperature approach, in essence, ensured that more energy could be extracted from the building via the fourth hole to the baghouse, resulting in improved building conditions.

APC Upgrade Options

Upgrades to the air pollution control system can take two forms: a full upgrade of the entire gas cleaning system to match the production increase, or alternatively optimization of the system through a high-temperature approach.

Full APC System Upgrade — A full upgrade can include replacement or upgrade of the following items:

- Replacement of canopy ducting to mixing chamber.
- Replacement of fourth-hole extraction water-cooled ducting and combustion chamber.
- Upgrade of trombone cooler by adding tubes and increasing tube length.
- Adding compartments to the baghouse.
- Moving the fans and stack to allow for baghouse extension.
- Speeding up existing fans or installing additional fans.
- Replacing the stack to allow for increased volumetric flow.

Brownfield site factors, not to mention loss of production, can be expected to increase capital expenditures by far more than the nominal upgrade factor of (in this case) 30% of the initial installed APC cost.

High-Temperature Approach — The high-temperature approach can offer a more cost-effective upgrade option through the following:

- Replacing polyester bags with high-temperature bags.
- Increasing booster fan speed to maximum rpm to adequately ventilate the furnace during the hottest part of the refining period.
- Trombone cooler may have to be augmented to allow for additional flow.

In order to allow for increased fourth-hole extraction, alternative filter materials should be evaluated. Fiberglass material is known to have many advantages:

- Non-combustible, as it is completely inorganic.
- Zero moisture absorption; therefore, it is not subject to hydrolysis.
- Dimensional stability (low coefficient of linear expansion).
- Very high strength but poor resistance to flex and abrasion; however, there are chemical surface treatments that improve the flex and abrasion characteristics of fibreglass.
- Woven fiberglass can operate continuously up to 260°C and depending on the surface treatment withstand up to 288°C for short periods.[6]

Person[7] has explained the relatively high filter drag of conventional woven fiberglass material when applied to metallurgical fume. Additionally, one could reasonably expect higher particulate emissions through the conventional fiberglass filter media, since the filter cake must be sacrificed to maintain airflow. While aramid material (good to 204°C) in shaker cleaning applications shows lower filter drag than woven fiberglass material, there is limited experience with aramid in EAF baghouses. Furthermore, in the limited cases where aramid had been used in EAF applications, the results have not been encouraging.

Eriksen[8] and Stordahl[9] reported that GORE® membrane/fiberglass filter media has substantially lower filter drag than conventional media in metallurgical fume applications. Previous work by Hall et al.[10] demonstrated the improved filtration efficiency of GORE membrane filter bags in a steel EAF application at British Steel when compared to the results with various woven synthetic filter media at the same installation.

Conclusions

The results of test work, offgas calculations and CFD modelling led to the following conclusions:

- Test results indicated that:
  - Furnace normalized extraction decreased as furnace gas temperature increased, resulting in less extraction at the hottest part of the heat and poorer fume extraction performance.
  - An increase in booster fan speed increased the normalized extraction rate, offgas temperature and offgas energy. Baghouse inlet temperature was, however, a limiting factor due to the maximum operating temperature of polyester bags. Full furnace evacuation could not be achieved.
- Offgas modeling calculations indicated a furnace duct extraction volume of 225,000 Nm^3/hour was required to ensure efficient capture of furnace offgas and minimize fugitive emissions. At this operating point, predicted baghouse inlet temperature was 154°C, well above the polyester operating range.
- CFD modeling indicated the following:
  - The effect of increased production rate on extraction efficiency, and therefore building air quality, was not as substantial during charging as it was during melting.
  - CFD results indicated that deteriorating building air quality is due mostly to fugitive fumes generated during melting.
  - Increasing the canopy extraction as well as the fourth-hole extraction, while staying within the polyester operating range, improved building air quality, but did not offer an acceptable solution.
  - A high-temperature approach, extracting most of the offgas energy from the furnace and limiting the amount of fume released to the canopy hood, resulted in good building air quality.
- For any meltshop suffering from fugitive emissions caused by production increases, various options for offgas system upgrade are available:
  - Full APC system upgrade, including replacement of large sections of ducting, adding baghouse compartments, installing additional fans and replacing the stack.
  - The high-temperature approach can offer a more cost-effective upgrade option by replacing polyester bags with high-temperature membrane bags, increasing booster fan speed to maximum rpm to adequately ventilate the furnace during the hottest part of the refining period, and augmenting the trombone cooler.
- Further benefits of the high-temperature approach include:
  - Reduced fugitive emissions and flames escaping from the furnace, thereby improving building air quality.
  - A cleaner and cooler meltshop, resulting in less wear and tear on furnace equipment and lower ambient dust levels.

The techniques of APC system performance testing, offgas modeling calculations and CFD modeling allowed a full evaluation of an existing installation. Changes in furnace operating parameters could be related back to fourth-hole extraction requirements and proposed APC system performance, as well as its effect on building air quality. The result is a comprehensive approach to the meltshop air pollution problem.

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This paper was presented at AISTech 2008 — The Iron & Steel Technology Conference and Exposition, Pittsburgh, Pa., and published in the Conference Proceedings.

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